Nonlinear gauge interactions - A solution to the "measurement problem" in quantum mechanics?

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Abstract

We propose that the mechanism responsible for the "collapse of the wave function" (or "decoherence" in its broadest meaning) in quantum mechanics is the nonlinearities already present in the theory via nonabelian gauge interactions. Unlike all other models of spontaneous collapse, our proposal is, to the best of our knowledge, the only one which does not introduce any new elements into the theory. Indeed, unless the gauge interaction nonlinearities are not used for exactly this purpose, one must then explain why the violation of the superposition principle which they introduce does not destroy quantum mechanics. A possible experimental test of the model would be to compare the coherence lengths for, *e.g.*, electrons and photons in a double-slit experiment. The electrons should have a finite coherence length, while photons should have a much longer (in principle infinite) coherence length.

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We start by noting an apparent paradox in the presently most fundamental description of (experimentally tested) physical reality.

- 1) The absolute backbone of quantum mechanics is the *superposition principle* [1] (*e.g.*, interfering amplitudes, summation of Feynman diagrams, etc). It is also well known that superposition requires *linear* equations (*i.e.*, the sum of two different solutions to a nonlinear equation is generally *not* a solution, ruining superposition). The Hilbert space of quantum mechanics and the Fock space of quantum field theory are *linear* spaces (based on the superposition requirement), suitable for linear mappings or operators.

- 2) Nonabelian gauge field theories describing the fundamental interactions obey *nonlinear* evolution equations in the gauge fields. This is in apparent contradiction to point 1). For convenience, we write down the evolution equations for pure Yang-Mills fields below. Although the fermion evolution obeys linear equations, they become "contaminated" by nonlinearities through the interaction.

The nonabelian vector gauge fields are governed by a set of coupled, second order, nonlinear PDEs on Minkowski spacetime. (The general argument for gravity is the same, but involve tensor fields on a dynamical spacetime. We do not explicitly write down those equations.) For pure Yang-Mills the evolution equations are given by the following formula,

$$(\partial^\mu - g[A^\mu, \,])_a^b(\partial_\mu A_\nu - \partial_\nu A_\mu - g[A_\mu, A_\nu])_b = 0, \tag{1}$$

where g is the coupling constant and a, b are indices of the gauge group (*i.e.*, $a, b \in 1,2,3$ for $SU(2)$ and $a, b \in 1,...,8$ for $SU(3)$). Summation over repeated indices is implied. The operator ("covariant derivative") at the left works according to $(\partial^\mu - g[A^\mu, \,])(anything) = \partial^\mu(anything) - g[A^\mu, anything]$. We see that we get highly nonlinear (quadratic and cubic) terms in the gauge fields, especially when the coupling constant, g, is large. The commutator terms (square brackets) vanish identically for abelian fields (*e.g.* photons) because the gauge fields then commute, leaving only the ordinary, linear Maxwell equations.

In the Feynman path-integral formulation of quantum mechanics [2] the nonlinearities can be "hidden" in the action functional, but as the Schrödinger, Heisenberg and path-integral formulations are equivalent, a problem in one of them must translate into a problem in all formulations.

Instead of trying to reconcile the two apparently contradictory statements above (by, for instance, modifying the rules of quantum mechanics), introduced by nonabelian gauge fields, we instead propose to turn a vice into a

virtue by postulating that it is the dynamical nonlinear interaction terms which break the superposition of different quantum states of a system, *i.e.* acting as the physical mechanism which reduces the state vector, or "collapses the wave function" in the less general Schrödinger setting. We thus get a self-induced collapse - "SIC", into the ordinary world of chairs, tables, people and indeed also recorded elementary particle tracks in a photographic emulsion, a bubble chamber, or a modern multi-purpose computer-aided detector.

That a quantum mechanical state must be able to "self-decohere" is imperative in quantum cosmology, the quantum mechanical treatment of the whole universe, where no "outside" observer exists. The self-induced collapse puts an end to the infinite regress of quantum superposition, where first the measuring apparatus obtains a quantum mechanical nature, then the observer, and so on, ad infinitum, until the whole universe consists of infinitely many superimposed quantum states, without any one of them actually being "realized". The "many worlds" interpretation of Everett [3] purports to solve this problem by assuming that we only see events which take place in one of these branching universes, but it seems that the fundamental question of *when*, and how, the universe actually branches is unanswered by that model (this being the equivalent of the "measurement problem" in the orthodox interpretation).

We now turn to the actual implementation of our idea of self-induced collapse. For simplicity, we choose the following (non-covariant) expression for the (average) self-decoherence time.

$$\tau = \frac{\hbar}{E_{N.L.}}, \tag{2}$$

where $E_{N.L.}$ is the energy stored in the nonlinear field configuration of the nonabelian interaction (which in turn depends on the strength of the coupling). Observe that the relation is *not* an uncertainty relation, despite its identical form, as τ and $E_{N.L.}$ are not uncertainties. As we want the energy of the full nonlinear theory, and we cannot today explicitly calculate this inherently non-perturbative quantity, we take the energy to be a characteristic energy for the interaction. If, for instance, for QCD, we as a rough approximation take the energy to be $E_{N.L.} \sim \Lambda_{QCD} \sim 0.2$ GeV, we get as a rough "ballpark" figure $\tau_{QCD} \sim 10^{-23}$s for the decoherence time for *strong* QCD (*e.g.*, inside a non-disturbed hadron). Although the exact result probably will differ by many orders of magnitude, this may explain

why (semi-)classical models work so well for strong QCD, as the stronger the interaction is, the more "classical" it behaves according to our mechanism. In QCD the energy stored in gauge fields decreases as the absolute energy of the interaction increases, due to asymptotic freedom.

In our model, the *fields* are the fundamental entities which obey quantum mechanics, the particle aspect appearing each time a self-collapse takes place. That is, the quantum mechanical (linear, unitary) evolution is constantly punctuated by (possibly random) "hits" of self-collapse at an average frequency of τ^{-1}. This is similar to the case in orthodox quantum mechanics where an observation (or the initial preparation of a state) suddenly "realizes" one of the potential outcomes, after which the unitary (linear) evolution of the state takes over until the next observation. A "macroscopic" piece of matter has such a high energy stored in nonlinear field configurations that $\tau = \frac{\hbar}{E_{N.L.}} \sim 0$, approximating a continuously collapsing state, *i.e.*, a classical state. The model thus forbids quantum mechanical effects to "invade" the macroscopic world, and hence resolves the "Schrödinger's cat" paradox [4] and related questions such as "Wigner's friend" [5], etc.

Note that *any* significant nonlinear interaction, whether as part of a "measurement" carried out by conscious beings [4, 5] or not, bring about the decoherence of interfering amplitudes into (semi-)classical states. Conscious observation is therefore only a *special case* of the more general nonlinearity, as all "measuring apparatuses" (including human beings!) consist of both weakly (all particles) and strongly (quarks) nonlinearly interacting constituents. Hence, there should be no need to introduce the *mind* into the interpretation of quantum mechanics at a fundamental level.

For pure QED the nonlinear terms are absent, hence a hypothetical world built by QED alone would never be classical. It also explains why, *e.g.*, atomic physics works so closely to orthodox quantum mechanics, as it is being "classicalized" only by (very) weak interaction effects. Were it not for the existence of the other interactions besides QED, we would indeed have quantum mechanical superpositions of whole universes, *i.e.*, the "many worlds" interpretation of quantum mechanics by Everett [3].

The difference between our proposal for self-induced collapse, and other models aiming at the same goal, is that, as far as we know, all other models postulate additional equations and/or variables,

- Decohering histories [6, 7]: new fundamental principle of irreversible coarse graining + additional constraints to remove "too many" deco-

herent histories

- Altered Schrödinger equation: obvious extra (non-unitary[8] or nonlinear[9]) term in Schrödinger equation

- Bohm QM [10]: additional (nonlinear) evolution equation for objective positions

whereas we use only nonlinearities which are *already present* in the dynamics of the accepted standard model of particle physics. Another difference is that, to our knowledge, all other models for spontaneous collapse are non-relativistic, whereas our scheme is based on covariant theories. Also, it must be stressed that if the nonlinearities introduced by the nonabelian gauge fields are *not* used to explain the decoherence to (quasi)classical behaviour, it must instead be explained how they can be reconciled with the superposition principle of quantum mechanics.

It is well known that a nonlinear mapping is non-reversible, as there in that case does not exist a unique inverse mapping (*i.e.*, the mapping is not one-to-one). We therefore propose that the nonlinear gauge interaction is the physical "mechanism" of the "irreversible amplification" emphasized by Bohr as being necessary to produce classical, observable results from the quantum mechanical formalism. Even though Bohr himself denounced the need, or even the possibility, to give a physical description of this "mechanism" [11], we believe that the central problem for truly understanding quantum mechanics lies in the quantum measurement problem. For instance, it is *only* there, in the collapse of the wave function, that the undeterminacy of quantum mechanics enters. It may even be possible, if not entirely likely, that deterministic chaos in the nonlinear self-interaction can be responsible for the seemingly statistical character of quantum mechanics.

Our model can be experimentally tested, at least in principle, as differently charged (electric, weak isospin, color,...) particles should have different coherence lengths. In a double-slit experiment, for instance, the photon should have a much longer (in principle infinite) coherence length than, *e.g.*, electrons which ought to have a finite coherence length due to nonlinear weak interactions. As the full nonlinear calculations are very complicated, it is not possible to quantitatively predict the coherence lengths at the present time, but if it turns out that electrons experimentally have shorter coherence lengths than photons it would strengthen our hypothesis.

Our model could also have importance for (the not yet existing theory of) quantum gravity. Weak gravity would have extremely long decoherence times, completely swamped by the other interactions. However, exactly where quantum gravity is expected to become important (*i.e.*, at the Planck mass/energy scale), we see that it spontaneously decoheres. Hence a strong *quantum* gravity might not exist in this scheme.

The collapse postulated in orthodox quantum mechanics is not relativistically covariant, as it is instantaneous (over all space), which is not a covariant concept. Only the (deterministic) unitary development of the state is taken into account by the relativistic Dirac equation and, more generally, by quantum field theory. As our scheme for collapse is based on covariant gauge-field theories, it might be possible to describe the collapse of the state in a covariant way, although our present attempt, which for *simplicity* singles out the energy accumulated in the nonlinear field configurations, is not covariant. On the other hand, it might be that the collapse should be described by an inherently non-local mechanism, as it seems that quantum mechanics at its very foundation *is* non-local, as given by the results of Aspect *et al.* [12], and more recent experiments on quantum non-separability. As a nonlinear theory also in some cases can be non-local, it would be interesting to investigate if this model of spontaneous collapse can account for such non-local effects. Work in this direction is in progress [13], together with a detailed investigation of the nonlinear terms in the nonabelian evolution equations, as a means to better understand the quantitative details of the proposed mechanism for self-collapse.

In conclusion, we have emphasized that automatic dynamical collapse of the wave function in quantum mechanics may already be implicit in the existing dynamical theory of nonabelian (*i.e.*, nonlinear) gauge fields. These include the weak interaction, QCD, gravity, and any other nonabelian fields which eventually may be found in the future. The nonlinear self-interaction terms break the fundamental superposition principle of quantum mechanics, hence making it plausible that they can be just the right physical mechanism for the purpose of collapse.

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